Very high resolution soft x-ray spectrometer for an electron beam ion trap

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A very high resolution vacuum flat-crystal spectrometer was constructed for analyzing soft x rays emitted by an electron beam ion trap. The spectrometer was designed to operate at large Bragg angles ($\theta \leqslant 85°$) in order to maximize the spectral dispersion and thus the resolving power. Using a quartz (100) crystal at a Bragg angle of 82°, a measurement of the $2p_{1/2}$, $2p_{3/2} \rightarrow 1s_{1/2}$ transitions in hydrogenic Mg^{11+} situated near 8.42 Å was made. The nominal resolving power of the instrument was better than 30 000 allowing us to infer the ion temperature (246 ± 20 eV) from the observed line widths. A comparison with an existing flat-crystal spectrometer demonstrates the great improvement in resolving power achieved. [S0034-6748(97)67701-1]

I. INTRODUCTION

Recently, it was shown that the temperature of the ions confined in an electron beam ion trap (EBIT) can be much lower than the energy of the electron beam used to produce and excited the ions. Temperatures as low as 70 eV were measured for Ti^{20+} ions excited by 4.0 keV electrons.[1,2] The measurements were made using very high resolution crystal spectrometers in the von Hámos geometry operating in a helium atmosphere.[3,4] These spectrometers were sensitive to x rays with wavelength less than 5 Å. In order to perform measurements of the ion temperature of low-Z ions which emit x radiation in the wavelength region above 5 Å, very high resolution instruments are necessary that operate *in vacuo* to avoid x-ray absorption by air. In the following, we describe the design and operation of such a spectrometer and use it to determine the temperature of Mg^{11+} ions excited by 5 keV electrons. The measurements demonstrate significant improvements in resolving power over existing flat-crystal spectrometers and illustrate that very precise, high-resolution spectral measurements are possible with the new instrument in the soft x-ray range above 5 Å.

II. SPECTROMETER DESIGN

Compared to many high-temperature plasma sources the EBIT device is a relatively weak x-ray source, and efficient recording of x rays is a necessity. The EBIT device employs a compressed electron beam to excite electrostatically trapped ions.[5] X rays are emitted from the region in which the ions interact with the electron beam. The dimensions of this region are determined by the 2 cm length of the trap and the 60 μm diameter of the electron beam. The source dimensions are thus slitlike and well matched for a flat-crystal spectrometer, and such a spectrometer has been in successful operation for several years on EBIT.[6] This flat-crystal spectrometer operates *in vacuo* and is sensitive to x rays with wavelength above 5 Å.[6] The instrument, however, affords a resolving power $\lambda/\Delta\lambda$ which is typically less than 2000. In designing a new, very high resolution vacuum-type spectrometer, we have kept the basic design of the existing EBIT flat-crystal spectrometer, while greatly increasing the range of attainable Bragg angles.

Crystal spectrometers obey Bragg's law:

$$n\lambda = 2d \sin \theta. \tag{1}$$

Here d is the lattice spacing of the crystal and n is the order of reflection of a line with wavelength λ at a Bragg angle θ. Consequently, the resolving power of a spectrometer is given by

$$\lambda/\Delta\lambda = \tan \theta/\Delta\theta, \tag{2}$$

where $\Delta\theta$ represents the angular resolution of the instrument. An increase in the resolving power can be achieved in two ways, either by decreasing $\Delta\theta$ or by increasing $\tan\theta$. The angular resolution $\Delta\theta$ is a function of the spatial resolution of the detector, the source width, and the resolving power of the crystal, and generally is inversely proportional to the overall dimensions of the spectrometer. The resolving power of the spectrometer can thus be improved by increasing the overall dimensions of the instrument. The value of $\tan\theta$ can be increased by measuring at large Bragg angles. Especially desirable is to operate the spectrometer at Bragg angles approaching 90° where $\tan\theta \rightarrow \infty$. In the design of our new high resolution flat-crystal spectrometer, we have implemented both options. We increased the overall dimensions of the

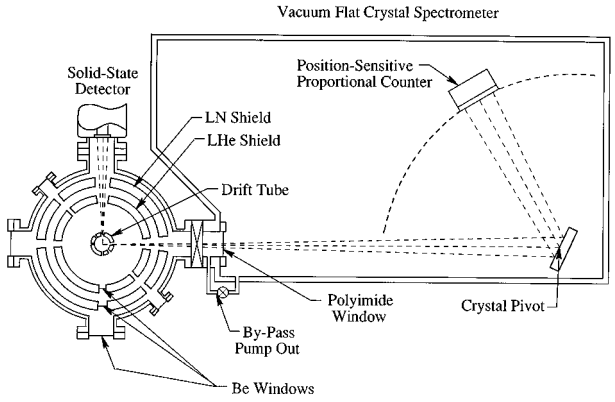

FIG. 1. Schematic layout of the new flat-crystal spectrometer on the EBIT facility. The electron beam direction is out of the page and represents a 60-μm-wide line source so that no entrance slit is needed. Crystal and detector rotate about a common pivot point at the opposite end of the entrance port. This permits setting the detector to Bragg angles as large as 85°.

spectrometer and modified the existing EBIT flat-crystal spectrometer design to accommodate Bragg angles near 90°.

Figure 1 shows a schematic of the new high-resolution flat-crystal spectrometer. Like in the existing instrument,[6] the diffraction plane is oriented perpendicular to the electron beam. Easy alignment is achieved by rotating the crystal and position-sensitive detector around a common pivot point using a vacuum feedthrough. Unlike in the existing spectrometer, where the point of rotation is located next to the entrance port,[6] the point of rotation is located at the far end of the entrance port. As a result, it is possible to situate the detector at a Bragg angle as large as 85°. This contrasts with the existing spectrometer where the maximum attainable Bragg angle was 63°.[6] Moving the point of rotation further away from the entrance of the spectrometer also increases the distance between the EBIT source and the detector. In the present design, this distance is about 160 cm, which is an increase by a factor of 3. An increase in the total source-to-detector distance decreases the flux of photons reaching the detector. However, the decrease is compensated by operating at large Bragg angles, where the crystal reflectivity is enhanced. Like in the existing spectrometer, a free-standing, 25 mm-diam foil is used to separate the spectrometer vacuum (5×10^{-6} Torr) from the high vacuum of the EBIT vessel ($\sim10^{-10}$ Torr), and a by-pass pumpline (cf. Fig. 1) is employed during the evacuation of the spectrometer to maintain nearly equal pressure on both sides of the foil. We use either a 1 μm polyimide foil or a 0.5 μm mylar foil. These foils are sufficiently thin to allow detection of x rays with energies as low as the carbon K edge. The detector is similar to the one used in the existing flat-crystal spectrometer. Its spatial resolution is about 250 μm. Placing the detector 160 cm away from the EBIT source provides an angular resolution of $\Delta\theta=1.6\times10^{-4}$ rad and corresponds to a nominal resolving power $\lambda/\Delta\lambda=6400$ at a Bragg angle of 45°.

III. PERFORMANCE AND SPECTRAL MEASUREMENTS

To illustrate the performance of the new spectrometer, a measurement of the $2p_{1/2}$, $2p_{3/2}\rightarrow1s_{1/2}$ (Ly-α_1 and Ly-α_2, respectively) transitions in hydrogenic Mg^{11+} was made. The transitions are situated at $\lambda=8.424\,61$ and $8.419\,20$ Å, respectively.[7] For the measurement, we used a 2×4 cm^2 quartz (100) crystal with a lattice spacing $2d=8.5099$ Å. The spectrometer was adjusted to a nominal Bragg angle of 81.7° and the detector placed 25 cm away from the crystal. The distance between EBIT and the crystal was about 93 cm. The nominal resolving power at this Bragg angle thus was better than 30 000.

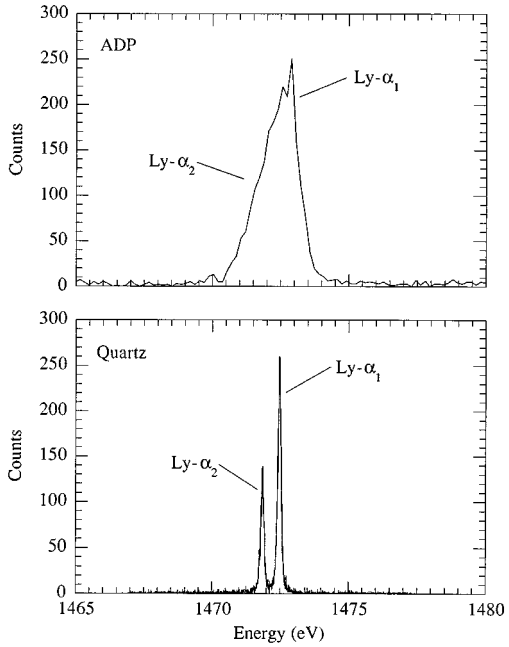

FIG. 2. Spectra of the $2p_{1/2},\rightarrow1s_{1/2}$ Ly-α_1 and $2p_{3/2}\rightarrow1s_{1/2}$ Ly-α_2 transitions in hydrogenic Mg^{11+}. The top spectrum was recorded with the existing EBIT flat-crystal spectrometer using an ADP (101) crystal at a Bragg angle of 52°. The bottom spectrum was recorded with the new EBIT flat-crystal spectrometer using a quartz (100) crystal at a Bragg angle of 82°.

Hydrogenic Mg^{11+} ions confined in a 200 V deep axial potential well were produced and excited in the EBIT device in the interaction with a 92 mA, 5.0 keV electron beam. The spectrum recorded with the new instrument is shown in Fig. 2. The two Ly-α lines are completely resolved. By contrast, we measured the same lines with the existing flat-crystal spectrometer. The resulting spectrum is also shown in Fig. 2. For this measurement, we used a 2.5×5 cm^2 ammonium dihydrogen phosphate (ADP) crystal cut to the (101) plane with a lattice spacing $2d=10.65$ Å. The corresponding Bragg angle was 52°. In this measurement, the two Ly-α lines are not resolved, although a slight asymmetry can be noted. The comparison between the two spectra in Fig. 2 illustrates the dramatic differences in resolving powers. This difference is in large part due to the differences in Bragg angle at which the measurements were made, as the ratio tan(82°)/tan(52°) provides an increase in resolving power by a factor of 5.5.

The width of the each of the two Ly-α lines is found to equal 2.23 mÅ. Assuming the width is the result of thermal Doppler broadening, we can determine the temperature T_i of the Mg^{11+} ions from the relation

$$T_i=1.6798\times10^8\ \mu\ (\Delta\lambda/\lambda)^2\ \ [\mathrm{eV}], \tag{3}$$

where μ is the mass of the ion in atomic mass units. For magnesium, $\mu=24.3$. We find $T_i=246\pm20$ eV from the measured line width after correcting for the intrinsic resolution of 1×10^{-4} of the quartz(100) crystal. To test the assumption that the broadening is indeed caused by thermal Doppler broadening, we injected germanium into the trap and studied the line emission from neonlike Ge^{22+}. The $3p_{1/2}\rightarrow2s_{1/2}$ transition in neonlike germanium falls in the same wavelength region as the two Ly-α lines,[8,9] and thus the germanium line can be measured with exactly the same spectrometer settings as the magnesium lines. Because germanium is heavier ($\mu=72.6$), we expect the observed width to be significantly smaller than that of the magnesium lines given the same temperature. Indeed, we find the width of the germanium line to be 1.66 mÅ, i.e., 0.57 mÅ less than that of the magnesium lines. This is not as small as expected if the ions from both elements have the same temperature, and it may indicate that the germanium line width is limited by the instrumental resolution or that the heavier, higher charged ions are indeed hotter, as expected from the fact that they are trapped more deeply than the magnesium ions. Nevertheless, the smaller line width for the germanium line validates our results for magnesium and proves the utility of the new spectrometer for making precise, high-resolution spectral measurements.

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